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MUZZLE BLAST AMPLIFICATION

Edward M. Schmidt

November 1976

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I. INTRODUCTION

Following separation from the gun tube and prior to entering undisturbed free flight, a projectile must traverse the muzzle blast field. Since this region is highly energetic, it is of interest to determine both the magnitude of gasdynamic forces acting on the round and their effect on the resultant trajectory. The development of the muzzle blast is obviously an unsteady phenomena; however, it has been demonstrated^{1,2} that the flow between the gun muzzle and the inward facing shock or Mach disc of the propellant gas jet may be treated as being quasi-steady¹ in nature. Based on this postulate, muzzle blast loadings upon fin-stabilized projectiles have been calculated^{3,4}.

Gretler³ assumes the quasi-steady core flow is adequately represented as a supersonic, spherical source. Fansler and Schmidt⁴ improve on this solution by treating the core as an axi-symmetric, underexpanded jet. While this produces an estimate of the muzzle blast impulse which is nearly twice that predicted by Gretler, the resultant contribution of muzzle blast induced jump to the overall dispersion of typical weapons is shown to be negligible.

Both models assume that the flow may be treated as quasi-steady, that body loadings may be neglected in comparison to those on fins, and that fin loads may be calculated using thin airfoil theory. Evaluation of the validity of these approximations requires comparison with experiment; however, detailed information on muzzle blast flow fields

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1. K. Oswatitsch, "Intermediate Ballistics," *Deutsche Luft und Raumfahrt* FB 64-37, December 1964. AD 473249.
 2. E. M. Schmidt and D. D. Shear, "The Flow Field About the Muzzle of an M-16 Rifle," BRL Report No. 1692, U. S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, January 1974. AD 916646L.
 3. W. Gretler, "Intermediate Ballistics Investigations of Wing Stabilized Projectiles," *Deutsche Luft und Raumfahrt* Report 67-92, FSTC-HT-23-22-69-72, 1967.
 4. K. S. Fansler and E. M. Schmidt, "The Influence of Muzzle Gas-dynamics upon the Trajectory of Fin-Stabilized Projectiles," BRL Report No. 1793, U. S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, June 1975. AD B005379L.

and loadings on projectiles is difficult to obtain. This author⁵ has reviewed some of the experimental techniques available and concludes that direct measurement of loadings transmitted to projectiles in transit of the muzzle region is not currently feasible. Rather, observations of the downrange dynamics of a round should be used to infer properties of the launch regime. Since the effects of gasdynamic loadings on downrange motion may not be separated from those due to mechanical loadings, it is necessary to introduce artificial constraints which hold one source of loadings constant while systematically varying the other.

This approach is taken in the present work. A muzzle device is designed to amplify the gasdynamic loadings experienced by a small caliber flechette round at launch. Two series of firings are conducted, one with and the other without the device attached. The resulting impact distributions are measured in each case. A calculation of the flow within the device and the loadings upon the round is performed using the approach of Fansler and Schmidt⁴. Comparison between the measured and predicted changes in impact distribution is used to establish the validity of the analysis.

II. EXPERIMENT

Tests are conducted using a 5.77mm smoothbore, Mann barrel firing the XM-645 single flechette round at a velocity of 1473 m/s. Pertinent physical properties of the gun and round are given in Table I. This system has been the subject of an intensive experimental survey⁶ of the launch dynamics of flechette projectiles. Data from this study will be used as input to the present study. The flow at the muzzle of the gun is modified by the addition of a muzzle adaptor, Figure 1.

The device is a nozzle which prohibits free expansion of the propellant gases. When the projectile separates from the muzzle, the propellant gases expand into the adaptor channel where they form a high pressure, high velocity stream over the projectile. A comparison of the centerline density variation in the free muzzle jet with the density distribution in the adaptor (calculated using quasi-one-dimensional theory), Figure 2, verifies this point. While free expansion in the muzzle jet brings about a rapid decay in centerline density, the density along the adaptor remains fixed at a relatively high level.

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5. E. M. Schmidt, "The Effect of Muzzle Jet Asymmetry on Projectile Motion," BRL Report No. 1756, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, January 1975. AD B002159L.
 6. E. M. Schmidt and D. D. Shear, "Launch Dynamics of a Single Flechette Round," BRL Report 1810, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, August 1975. AD B006781L.

To examine the effect of this variation in the launch environment on projectile trajectory, two groups of ten rounds were fired, respectively, with and without the muzzle adaptor in place. Impact distributions into a witness card placed 25 meters from the weapon muzzle were obtained, Figure 3. The measured dispersions in the horizontal and vertical directions are summarized below:

	σ_y (mils)	σ_z (mils)
Without Adaptor	1.27	1.30
With Adaptor	2.41	2.28

The increase in dispersion due to the presence of the adaptor is substantial. Since the adaptor is fabricated from aluminum and is installed on a stiff, rigidly mounted Mann barrel, the mechanical loadings are assumed to be invariant between configurations, and the observed increase in dispersion is interpreted as arising due to amplification of muzzle gasdynamic loadings. In the following section, the flow within the adaptor, gasdynamic loadings, and resultant trajectory perturbations will be calculated and compared with these results.

III. ANALYSIS

A. Flow Properties Within the Muzzle Adaptor

The conditions at the muzzle of the gun at shot ejection were calculated by B. Grollman⁷ of BRL. His predictions are tabulated below:

$$\gamma = 1.25$$

$$R = 399.2 \text{ m}^2/\text{s}^2 \text{ } ^\circ\text{K}$$

$$V_e = 1473 \text{ m/s}$$

$$T_e = 1540^\circ\text{K}$$

$$a_e = 877 \text{ m/s}$$

$$M_e = 1.68$$

$$p_e = 428.6 p_\infty$$

7. B. Grollman, Private Communication, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, July 1976.

To simplify the analysis, variation in the exit properties during projectile residence in the adaptor will be neglected.

Using steady, quasi-one-dimensional theory⁸, the computed exit conditions, and the area ratio of the device, $A/A_e = 4.0$, the flow properties within the adaptor may be calculated:

$$M = 2.95 , \quad (1a)$$

$$p/p_e = 0.114 , \quad (1b)$$

$$a/a_e = 0.805 . \quad (1c)$$

The relative Mach number with respect to the projectile is

$$\begin{aligned} M_r &= \frac{u-V}{a} = M - \frac{V}{a} \\ &= 0.863; \end{aligned} \quad (1d)$$

thus, flow over the projectile is transonic.

B. Projectile Loadings and Dynamics

Following Fansler and Schmidt⁴, transverse gasdynamic loadings upon the projectile are assumed to originate solely at the fins. Further, two-dimensional, thin airfoil theory will be used to compute the fin loadings under the assumptions that flow inclination, wing tip, and wing-body interference effects may be neglected. As a result, the following expression describes the transverse loadings on the round:

$$L = \frac{1}{2} \rho V_r^2 A_T C_{L_\alpha} \alpha, \quad (2)$$

where C_{L_α} is the lift coefficient on the fins in the reverse flow within the muzzle adaptor, Figure (4). For the relative Mach number in the adaptor, $M_r = 0.863$,

$$C_{L_\alpha} = 8.8.$$

8. H. W. Liepmann and A. Roshko, Elements of Gasdynamics, pp. 125-126, John Wiley & Sons, New York, 1957.

The gasdynamic moment about the projectile center of gravity is

$$M_t = \frac{1}{2} \rho V_r^2 A_T \ell C_{M_\alpha} \alpha . \quad (3)$$

Where the moment coefficient is related⁴ to the lift coefficient by:

$$C_{M_\alpha} = C_{L_\alpha} \frac{\Delta}{\ell} , \quad (4)$$

Δ/ℓ being the separation between the projectile c.g. and the fin c.p. in calibers.

Based on these loadings, the equations of motion for the projectile flight through the muzzle adaptor may be written:

$$m_p [dv/dt] = \frac{1}{2} \rho V_r^2 A_T C_{L_\alpha} \alpha , \quad (5)$$

$$I_t [d^2\alpha/dt^2] = \frac{1}{2} \rho V_r^2 A_T \Delta C_{L_\alpha} \alpha . \quad (6)$$

The independent variable in these equations may be transformed by noting

$$\begin{aligned} \frac{d}{dt} &= \frac{d}{d\bar{x}} \frac{d\bar{x}}{dt} \\ &= \frac{V_p}{\ell} \frac{d}{d\bar{x}} , \end{aligned}$$

where

$$\bar{x} = x/\ell ,$$

V_p = projectile velocity.

Thus,

$$m_p [dv/d\bar{x}] = \frac{1}{2} \rho V_r^2 A_T C_{L_\alpha} \frac{\ell}{V_p} \alpha , \quad (5a)$$

$$I_t [d^2\alpha/d\bar{x}^2] = \frac{1}{2} \rho V_r^2 A_T \Delta C_{L_\alpha} \frac{\ell^2}{V_p^2} \alpha . \quad (6a)$$

Since the flow properties in the adaptor are dependent only upon muzzle exit conditions (taken as constant) and assuming that the projectile axial velocity through the adaptor remains constant,

Equations (5a) and (6a) may be rewritten as

$$v'/V_p = n \alpha, \quad (7)$$

$$\alpha'' - m^2 \alpha = 0, \quad (8)$$

where

$$n = \rho V_r^2 A_T C_{L_\alpha} \ell/2 m_p V_p^2, \quad (9)$$

$$m^2 = \rho V_r^2 A_T \Delta C_{L_\alpha} \ell^2/2 I_t V_p^2. \quad (10)$$

For constant m^2 , Equation (8) may be solved directly:

$$\alpha = c_1 e^{m\bar{x}} + c_2 e^{-m\bar{x}}, \quad (11)$$

with boundary conditions at $\bar{x} = 0$

$$\alpha = \alpha_e,$$

$$\alpha' = \alpha'_e,$$

yielding

$$c_1 = \frac{1}{2} \left(\alpha_e + \frac{\alpha'_e}{m} \right), \quad (12)$$

$$c_2 = \frac{1}{2} \left(\alpha_e - \frac{\alpha'_e}{m} \right). \quad (13)$$

Substitution of Equation (11) into Equation (7) permits direct integration over the length of the muzzle adaptor, \bar{x}_L , giving

$$(v_L - v_e)/V_p = (n/m^2) (c_1 m e^{m\bar{x}_L} - c_2 m e^{-m\bar{x}_L} - \alpha'_e). \quad (14)$$

The projectile angular velocity at exit from the adaptor is obtained by differentiating Equation (11):

$$\alpha'_L - \alpha'_e = c_1 m e^{m\bar{x}_L} - c_2 m e^{-m\bar{x}_L} - \alpha'_e. \quad (15)$$

To specify the projectile dynamics upon entry into free flight, it is also necessary to consider the effect of transit of the adaptor muzzle blast, Figure 5. The flow properties along the centerline of the propellant gas jet are calculated using the method of characteristics⁹, Figure 6. The change in projectile dynamics is computed using the method of Fansler and Schmidt⁴, who show:

$$\delta (v/V_p) = (\gamma+1) P^* A_T \alpha_L \frac{D'}{m_p V_p^2} \bar{P} , \quad (16)$$

$$\delta (\alpha') = (\gamma+1) P^* A_T \alpha_L \frac{\Delta D \ell}{I_t V_p^2} \bar{P} , \quad (17)$$

where α_L is given by Equation (11),

$\delta()$ refers to an incremental increase in the bracketted property due to muzzle blast loadings,

$$\bar{P} = \int \bar{L} d\frac{x}{D} ,$$

$$\bar{L} = \frac{\gamma}{2(\gamma+1)} C_{L\alpha} \frac{\rho}{\rho^*} M_r^{*2} ,$$

$$D' = 2D = \text{diameter of muzzle adaptor.}$$

For the jet properties given in Figure 5,

$$\bar{P} = 0.24 . \quad (18)$$

Using the tabulated projectile and gun muzzle properties, Equations (11) and (14) through (18) may be used to determine the

9. A. R. Vick, et al, "Comparison of Experimental Free-Jet Boundaries with Theoretical Results Obtained with the Method of Characteristics," NASA TN D-2327, June 1964. NTIS N64-23032.

amplification of the projectile dynamics due to transit of the adaptor and its muzzle blast:

$$\frac{v_f - v_e}{v_p} = 0.056 \alpha_e + 2.31 \alpha_e' \quad (19)$$

$$\alpha_f' - \alpha_e' = 0.018 \alpha_e + 0.71 \alpha_e' \quad (20)$$

C. Dispersion Increase Due to Muzzle Adaptor

To compute the effect of the amplified muzzle gasdynamic loadings upon the projectile trajectory, it is necessary to know the distribution in initial projectile dynamics and the impact of this upon the resultant flight path. For the XM-645 round, the distribution of projectile dynamics at the muzzle was measured by Schmidt and Shear⁶, Table II. The amplification of this dynamic state due to transit of the adaptor may be calculated using Equations (19) and (20). Finally, the resultant trajectory perturbation is obtained by summing the aerodynamic¹⁰ and transverse linear momentum jumps:

$$\theta_T = \frac{\bar{C}_{L_\alpha}}{\bar{C}_{M_\alpha}} \frac{I_t}{m_p l^2} (\alpha_f' - \alpha_e') + \frac{v_f - v_e}{v_p} \quad (21)$$

where \bar{C}_{L_α} , \bar{C}_{M_α} are the lift and static moment coefficients of the projectile in forward flight.

Substitution of known projectile properties and Equations (19) and (20) into Equation (21) gives

$$\theta_T = -0.114 \alpha_e - 4.52 \alpha_e' \quad (22)$$

where θ_T is in milliradians for α_e expressed in milliradians and α_e' expressed in milliradians per caliber. Using Equation (22) and the distribution in α_e and α_e' , Table II, the increase in dispersion

10. C. H. Murphy, "Free Flight Motion of Symmetric Missiles," BRL Report 1216, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, July 1963. AD 442757.

due to presence of the muzzle adaptor is computed to be

$$\Delta\sigma_y = 0.4,$$

$$\Delta\sigma_z = 0.9.$$

A comparison of the predicted and measured results is given in Figure 7.

Considering the simplistic nature of the theoretical analysis and the crude nature of the experimental data, the comparison in Figure 7 is reasonably good. It demonstrates that the interpretation of the physical gasdynamics and the resultant loadings upon the projectile are within a better than order of magnitude agreement with the actual phenomena. Possible sources of error include data sample size, difficulties in predicting the flow properties both at the weapon muzzle¹¹ and within the adaptor (especially with transonic relative flow over the projectile), and the lack of treatment of sabot discard interactions.

IV. CONCLUSIONS

An experimental program was conducted which clearly demonstrates the possibility of amplification of muzzle gasdynamic loadings due to the presence of muzzle devices. By installing a muzzle adaptor with a length of 25 calibers and an inside diameter of two calibers (a geometry quite similar to that of a number of small arms muzzle devices, e.g., silencers), the round-to-round dispersion pattern of a 5.8mm flechette was increased from 1.25 milliradians to 2.25 milliradians. This one milliradian increase in dispersion is interpreted as arising solely due to increased propellant gasdynamic loadings upon the projectile during transit of the muzzle adaptor.

A theoretical analysis of these loadings is conducted using the approach of Fansler and Schmidt⁴. The predicted values of dispersion amplification are shown to agree reasonably well with the data. This is taken as a validation of the general correctness of the analytical approach.

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11. E. M. Schmidt, E. J. Gion, and D. D. Shear, "Acoustic Thermometric Measurements of Propellant Gas Temperatures in Guns," BRL Report 1919, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, August 1976. (AD #A030359)

Projectile Properties:

$$m_p = 6.8 \times 10^{-4} \text{ kg}$$

$$I_a = 3.2 \times 10^{-10} \text{ kg-m}^2$$

$$I_t = 7.1 \times 10^{-8} \text{ kg-m}^2$$

$$l = 1.8 \times 10^{-3} \text{ m}$$

$$\Delta = 1.78 \times 10^{-2} \text{ m}$$

$$n = 4$$

$$A = 1.0 \times 10^{-5} \text{ m}^2$$

$$A_T = nA/2 = 2.0 \times 10^{-5} \text{ m}^2$$

$$\bar{C}_{L_\alpha} = 15$$

$$\bar{C}_{M_\alpha} = -50$$

Weapon Properties:

Smoothbore

$$D = 5.77 \times 10^{-3} \text{ m}$$

$$L = 0.495 \text{ m} \quad (\text{overall})$$

$$m_c = 1.361 \times 10^{-3} \text{ kg} \quad (\text{ball powder})$$

$$V_c = 1.089 \times 10^{-6} \text{ m}^3$$

$$V_p = 1473 \text{ m/s}$$

TABLE I: PROPERTIES OF PROJECTILE AND WEAPON

ROUND	ANGLE OF ATTACK		ANGLE OF SIDESLIP	
	$\tilde{\alpha}_e$ (mr)	$\tilde{\alpha}'_e$ (mr/cal)	$\tilde{\beta}_e$ (mr)	$\tilde{\beta}'_e$ (mr/cal)
1	-7.42	-0.121	+2.46	-0.156
2	-0.56	-0.005	+1.95	-0.138
3	-1.84	-0.089	-3.74	+0.041
4	-0.40	+0.015	-0.44	+0.114
5	-1.30	-0.133	-0.03	-0.076
6	+3.99	+0.151	+1.90	-0.034
7	-0.68	-0.125	+3.72	-0.276
8	+3.64	+0.109	-4.50	+0.098

TABLE II: DISTRIBUTION IN LAUNCH ANGLE AND ANGULAR VELOCITY⁶

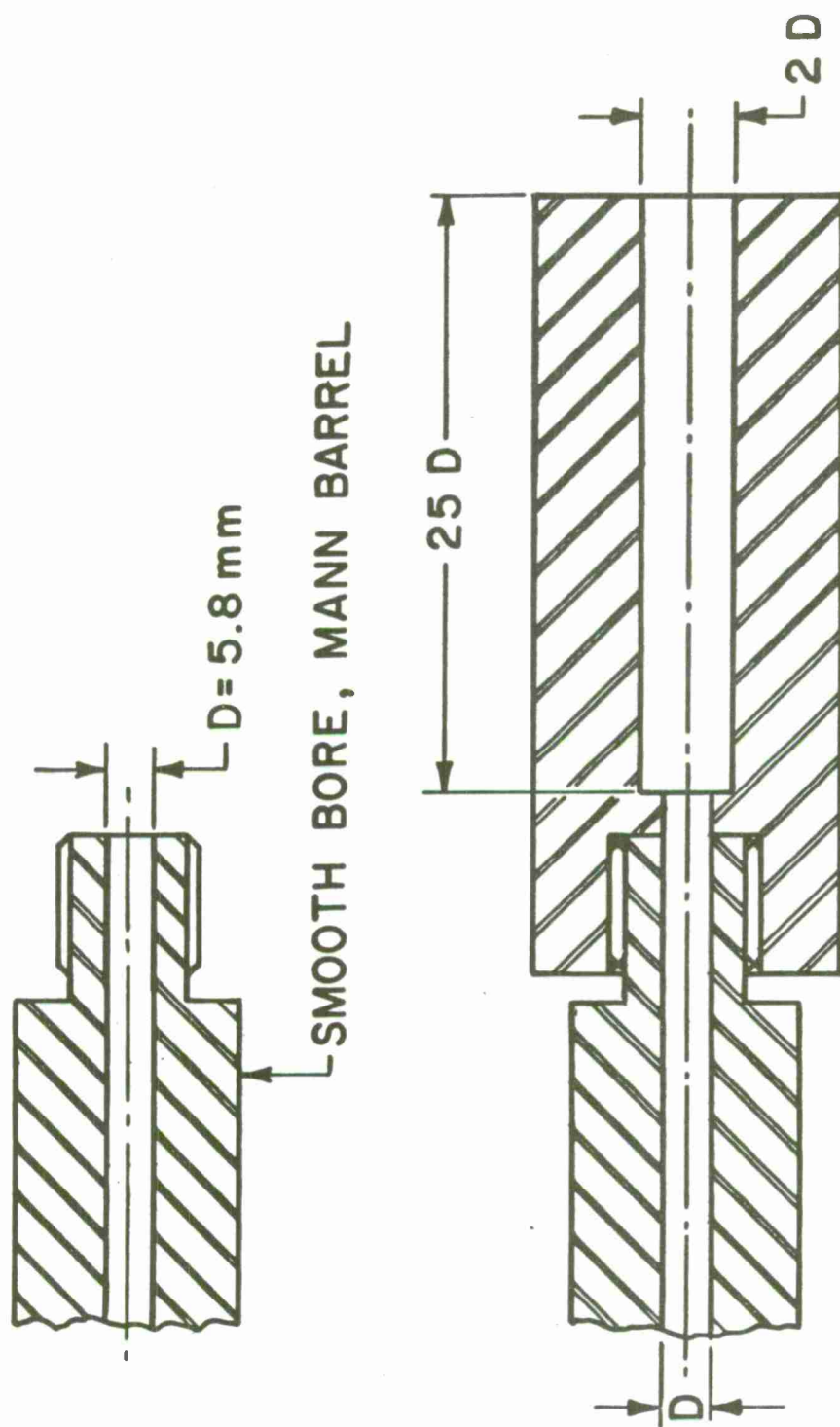


Figure 1. Schematic of Muzzle Adaptor

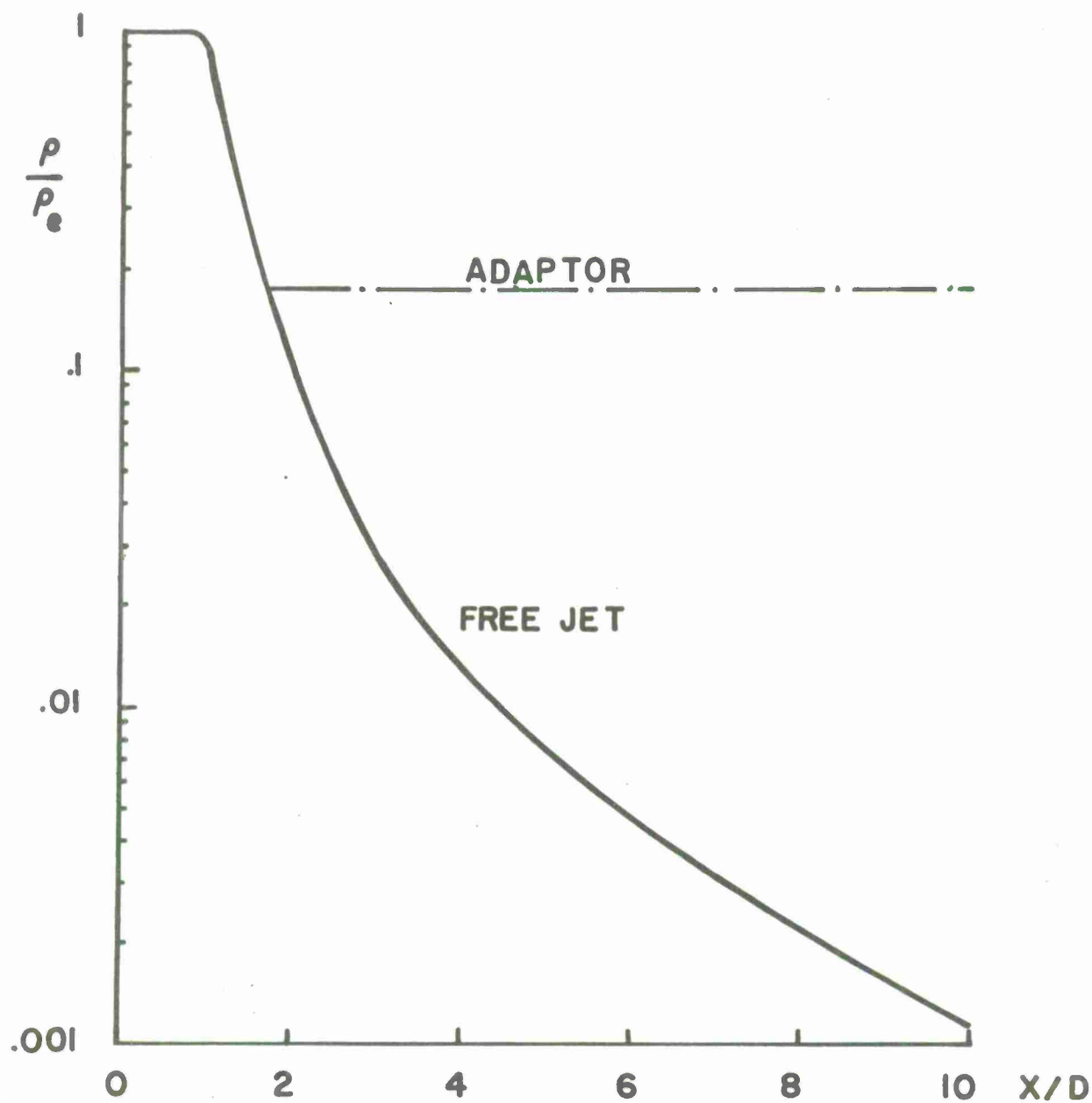


Figure 2. Comparison of Density Distribution Along Centerline of Adaptor and Free Jet, Both Expanding from Identical Exit Conditions.

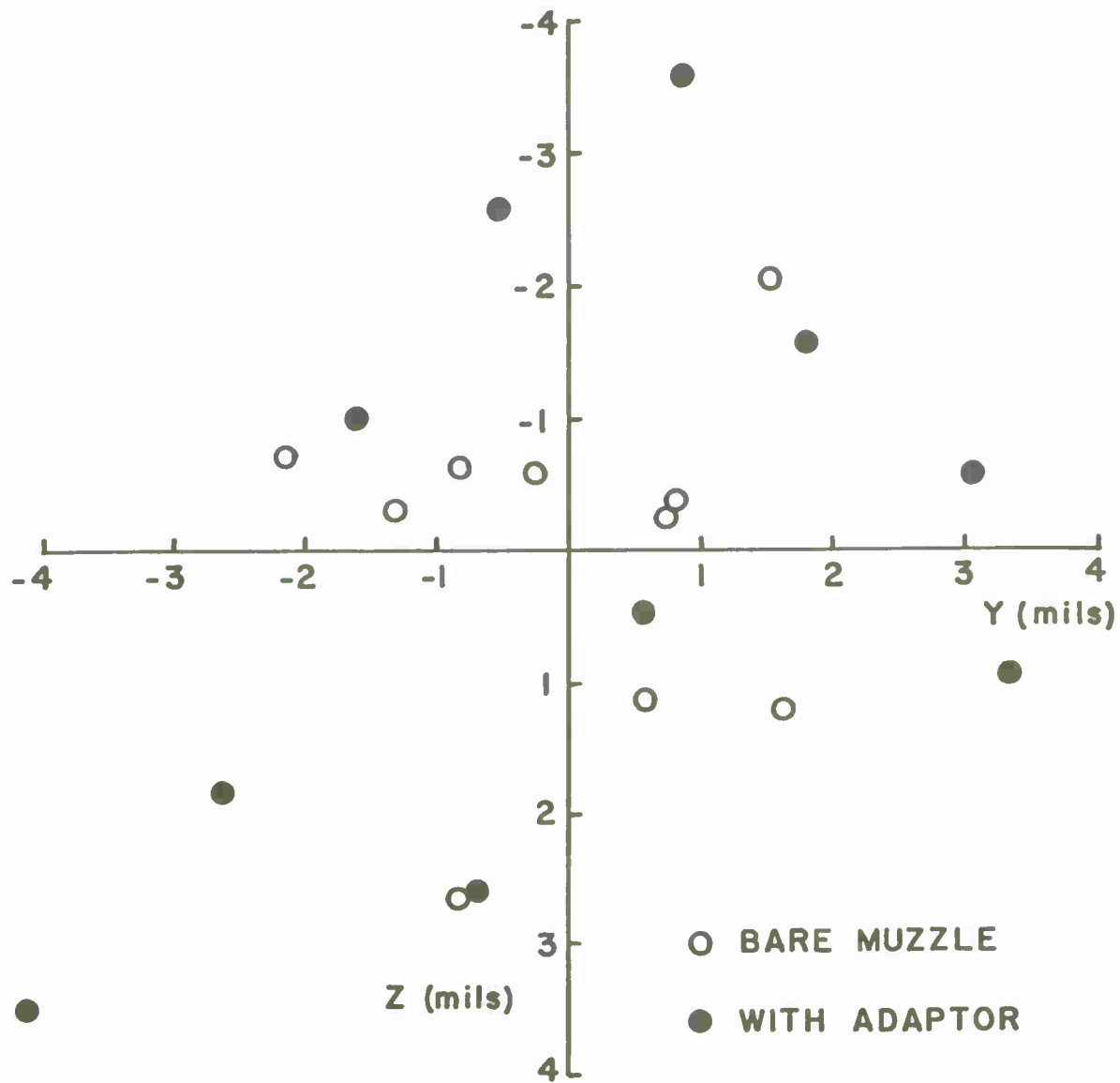


Figure 3. Measured Impact Patterns with and without Muzzle Adaptor.

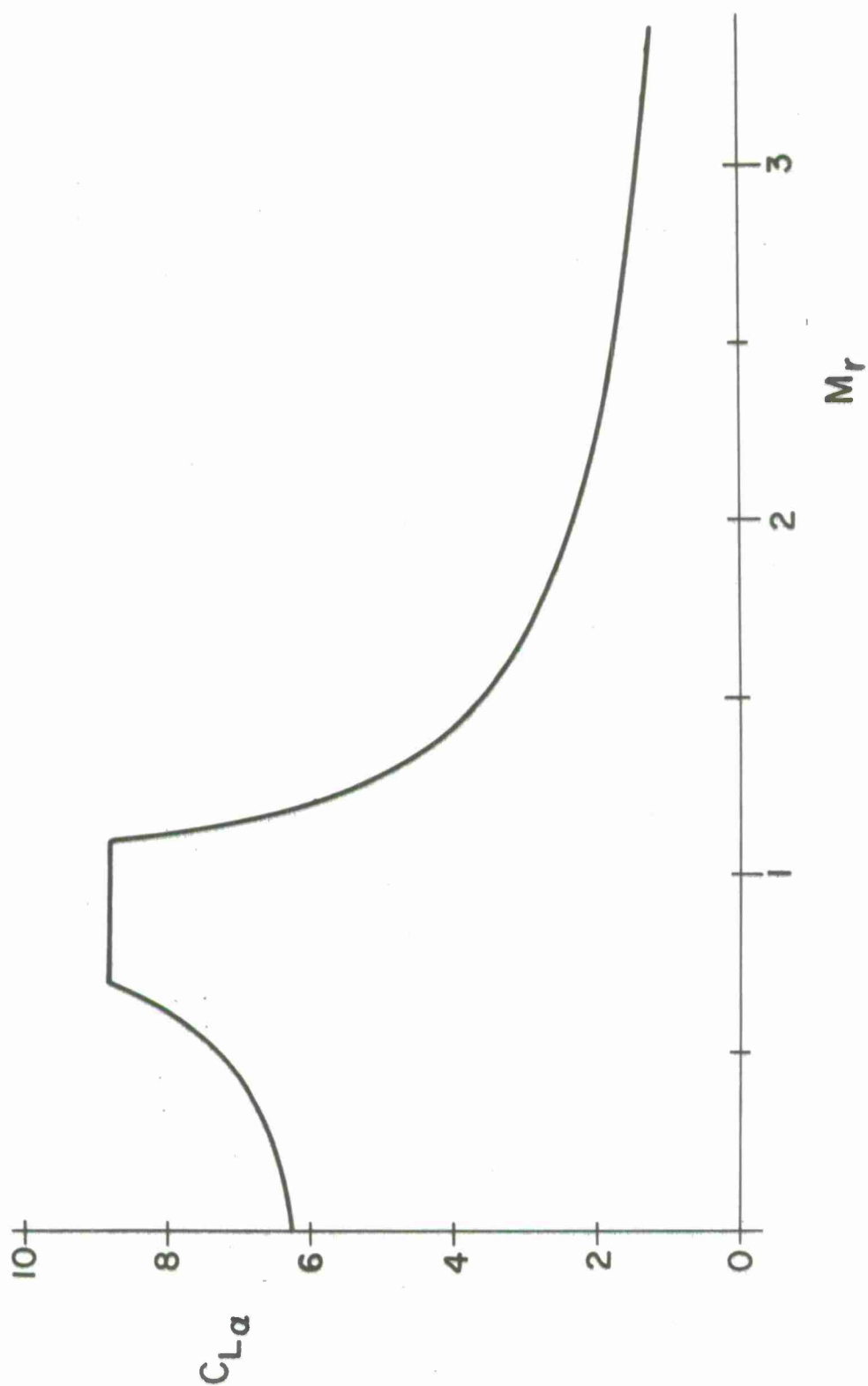


Figure 4. Fin Lift Coefficient Versus Relative Mach Number.

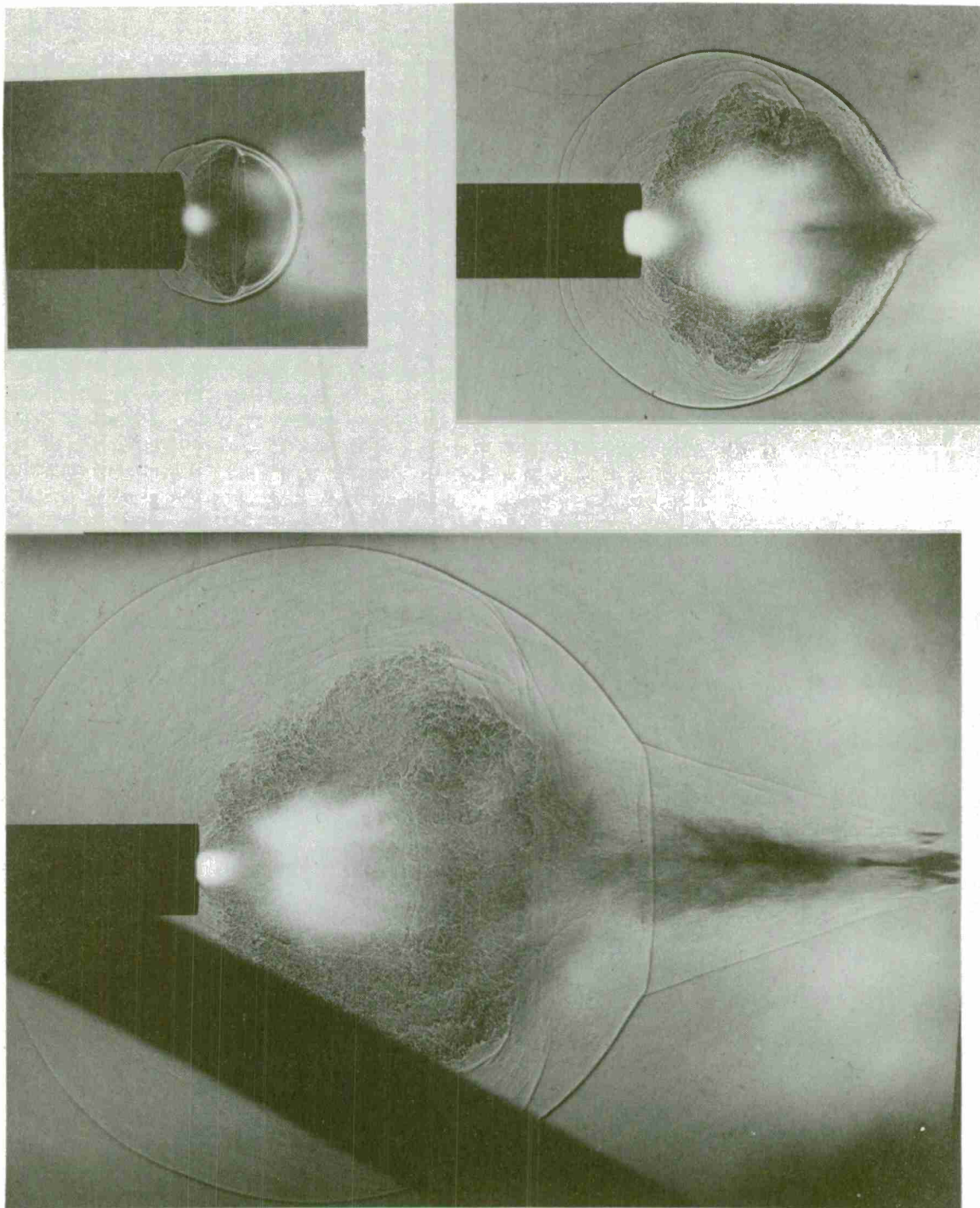


Figure 5. Spark Shadowgraphs of Muzzle Blast
from Weapon Equipped with Muzzle Adaptor.

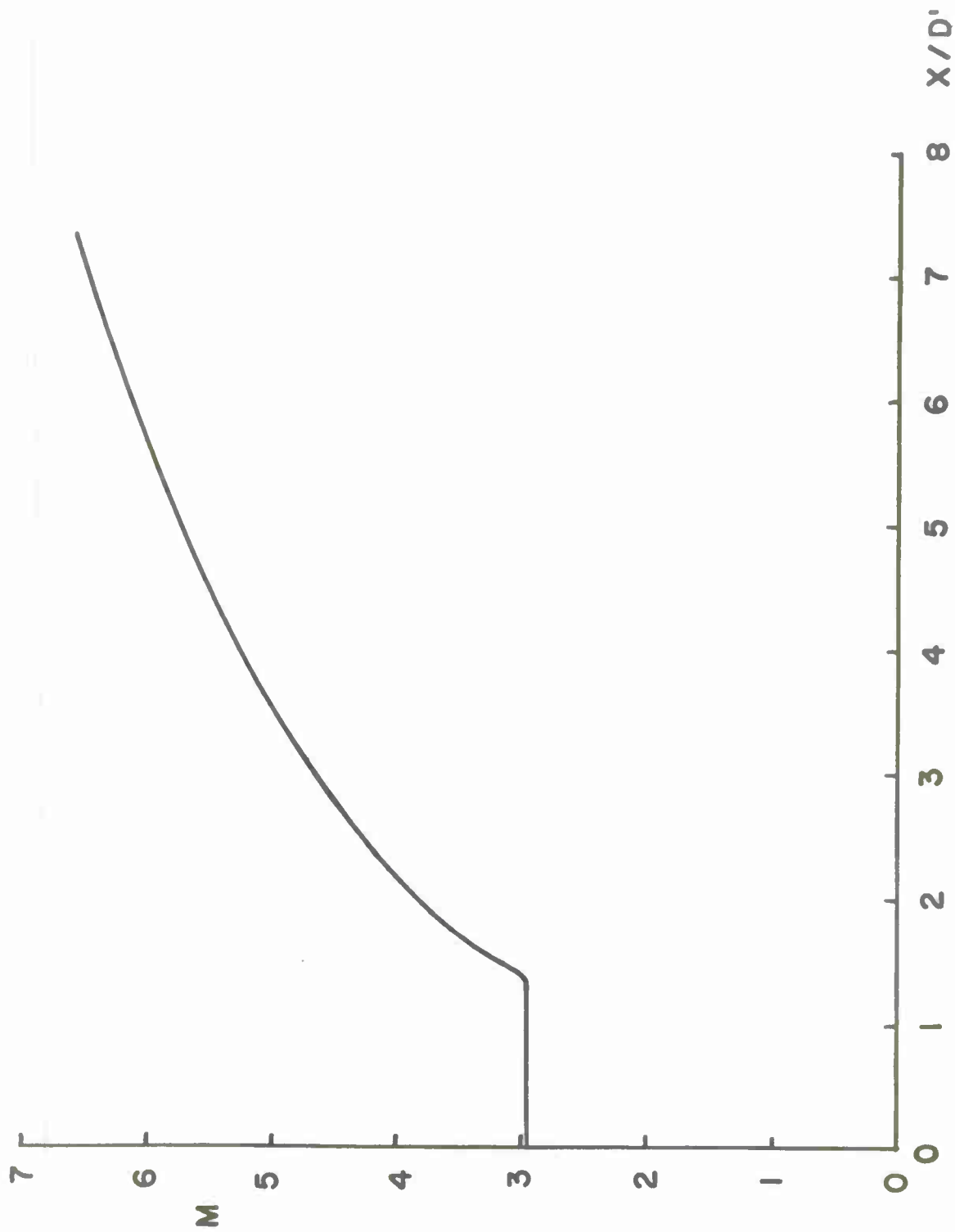


Figure 6. Mach Number Distribution Along Centerline of Underexpanded Jet where $M_e = 2.95$.

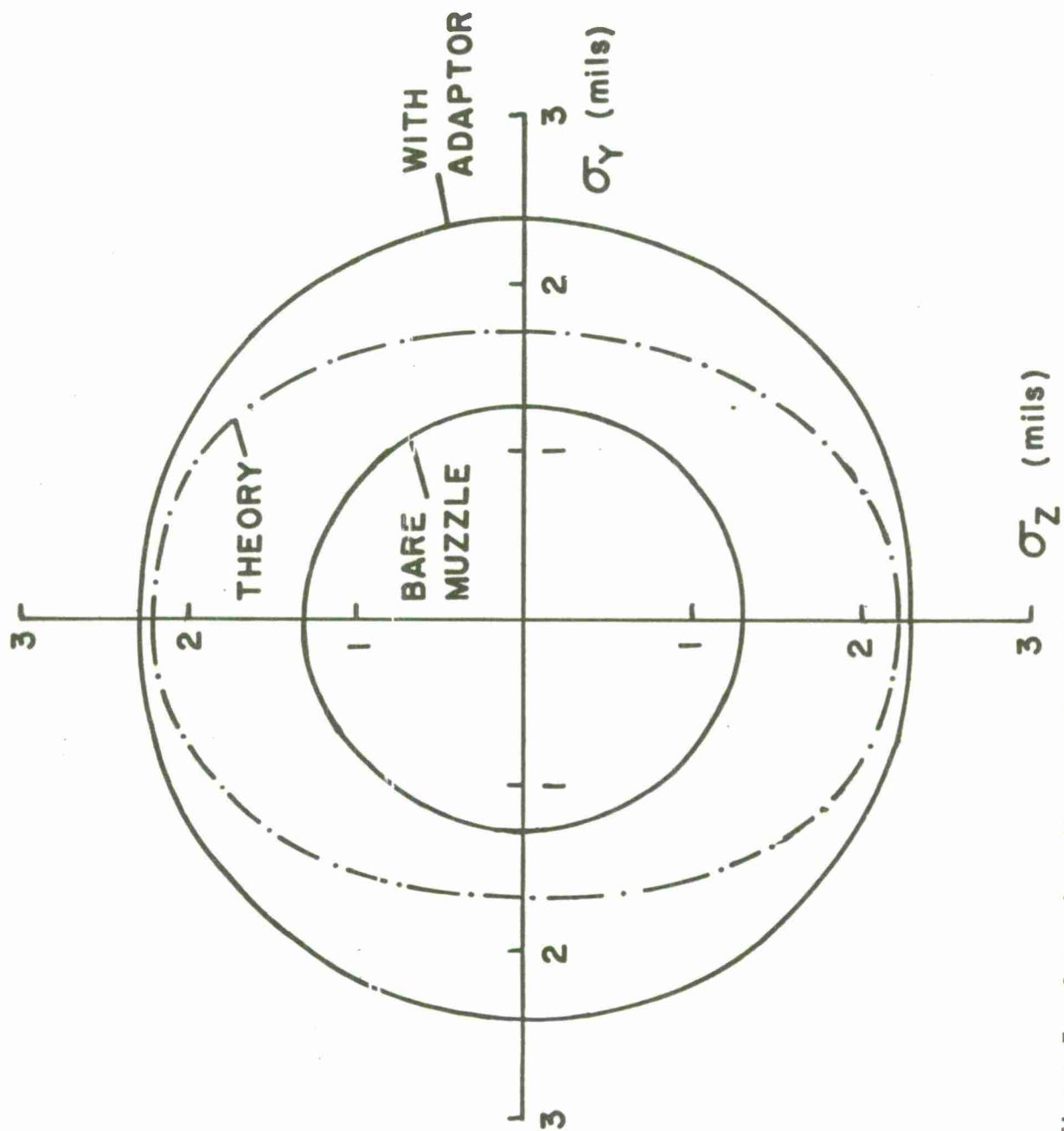


Figure 7. Comparison Between Theoretical and Experimental Impact Distributions.

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LIST OF SYMBOLS

a	speed of sound
A_T	equivalent fin area
$C_{L_\alpha}, C_{M_\alpha}$	lift and moment coefficients of fins in reverse flow
$\bar{C}_{L_\alpha}, \bar{C}_{M_\alpha}$	lift and moment coefficients of projectile in forward flight
D	gun tube diameter
D'	muzzle adaptor diameter ($D' = 2D$)
I_a, I_t	axial and transverse moments of inertia of projectile
ℓ	projectile (shaft) diameter
L	lift
\bar{L}	non-dimensional lift
m	coefficient defined in Equation (10)
m_p	projectile mass
M	Mach number
M_r	Mach number of reverse flow relative to projectiles
M_t	overturning moment
n	coefficient defined in Equation (9)
p	pressure
\bar{p}	momentum transfer function
R	gas constant
t	time
u	axial flow velocity
v	transverse projectile velocity
V_p	projectile launch velocity

x, y, z coordinate system: x directed downrange, y directed vertically downward, and z directed according to right hand rule.

α, β angles of attack and sideslip

γ ratio of specific heats

Δ c.p. - c.g. separation

θ_T total jump due to muzzle blast effects

ρ local flow density

σ_i one standard deviation in i

Subscripts

e muzzle exit conditions

r relative flow conditions

∞ ambient conditions

Superscripts

$()'$ spatial rate of change of property

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